Materials Science and Engineering C 55 (2015) 22–33

Contents lists available at ScienceDirect

Materials Science and Engineering C

journal homepage: www.elsevier.com/locate/msec

Study on torsional fretting wear behavior of a ball-on-socket contact configuration simulating an artificial cervical disk

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ARTICLE INFO

Article history:
Received 5 September 2014
Received in revised form 1 March 2015
Accepted 15 May 2015
Available online 21 May 2015

Keywords:
Torsional fretting wear
Ball-on-socket
Artificial cervical disk
In vitro simulation
Surface modification

ABSTRACT

A ball-on-socket contact configuration was designed to simulate an artificial cervical disk in structure. UHMWPE (ultra high molecular weight polyethylene) hot pressed by powders and Ti6Al4V alloy were selected as the material combination of ball and socket. The socket surface was coated by a ~500 nm C-DLC (carbon ion implantation-diamond like carbon) mixed layer to improve its surface nano hardness and wear resistance. The torsional fretting wear behavior of the ball-on-socket model was tested at different angular displacements under 25% bovine serum lubrication with an axial force of 100 N to obtain more realistic results with that in vivo. The fretting running regimes and wear damage characteristics as well as wear mechanisms for both ball and socket were studied based on 2D (two dimension) optical microscope, SEM (scanning electron microscope) and 3D (three dimension) profiles. With the increase of angular displacement amplitude from 1° to 7°, three types of T-θ (Torsional torque-angular displacement amplitude) curves (i.e., linear, elliptical and parallelogram loops) corresponding to running regimes of PSR (partial slip regime), MR (mixed regime) and SR (slip regime) were observed and analyzed. Both the central region and the edge zone of the ball and socket were damaged. The worn surfaces were characterized by wear scratches and wear debris. In addition, more severe wear damage and more wear debris appeared on the central region of the socket at higher angular displacement amplitude. The dominant damage mechanism was a mix of surface scratch, adhesive wear and abrasive wear for the UHMWPE ball while that for the coated socket was abrasive wear by PE particles and some polishing and rolling process on the raised overgrown DLC grains. The frictional kinetic behavior, wear type, damage region and damage mechanism for the ball-on-socket model revealed significant differences with those of a ball-on-flat contact while showing better consistency with that of in vitro cervical prosthesis simulations according to the literature.

1. Introduction

Total joint (hip, knee, cervical disk, lumbar disk, etc.) replacement is a well-established treatment option for treatment of degenerative disease [1]. Nowadays, there are several prostheses available and the use of artificial joints is becoming widespread. Unfortunately, prosthesis failure caused by wear and/or loosening of implant components occurs and the lifetime of orthopedic implants is just within 15–20 years [2]. Hence, prostheses with long-term life are becoming an important health issue because of aging people. To solve this problem, material design including surface coating and in vitro wear simulation are two of the most important factors for developing high-quality artificial prostheses.

In terms of material design, artificial joints generally consist of several implant components and are designed with different material combinations [3]. As metallic orthopedic and osteosynthesis materials, titanium alloys are generally believed more suitable for artificial joints due to their advantages in lower modulus, excellent corrosion resistance and superior biocompatibility compared with stainless steel and Co-alloys [4]. In addition, titanium alloys could also meet the imaging requirements (e.g. MRI (magnetic resonance imaging)) for artificial cervical disks when implanted [5]. However, poor tribological behavior of titanium alloys characterized by severe adhesive wear and low abrasion resistance limits their widespread use and long-term effectiveness [4,6–8]. In order to improve wear resistance and increase service life of titanium-based cervical disks or other artificial joints, different surface modification techniques have been developed [9]. Our group has also developed several coatings to solve this problem [6,10]. Among them, the mixing of C-DLC (carbon ion implantation and diamond like carbon) layers seems promising to improve wear resistance

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http://dx.doi.org/10.1016/j.msec.2015.05.056
0928-4931/

of titanium by strengthening the binding force of single diamond like carbon (DLC) and increasing the carbon ion implantation layer thickness. Hence, the mixed layer is coated on the titanium alloy surface to articulate with UHMWPE (ultra high molecular weight polyethylene) as the material combination of the artificial cervical disk in this study. However, considering that the focus of this research is on the in vitro wear simulation of an artificial cervical disk model, the details of micro-structure and coating properties compared with those of a single layer will be presented in another paper.

As known, artificial joints bear complex kinematics, a combination of rolling and sliding [11,12]. According to the literature [11–13], three different sliding modes (transversal, radial, and circumferential) have been defined in the hip joint. In contrast, there are also three angular movements (flexion/extension, lateral bending and axial rotation) for the artificial cervical disk [2]. So, torsional wear is one of the main motion modes for joints. And torsional fretting can be defined as the relative motion induced by reciprocating torsion under normal axial rotation movements for a cervical/lumbar disk or an oscillatory vibratory environment for other joints. Since torsional fretting wear is one of the main failure modes and may result in contact wear by detachment of particles and contact fatigue by rapid crack nucleation and propagation [14–16], experimental tests have been frequently reported in the literature during the past several decades [12–20]. However, the reported torsional fretting wear tests are mainly on contact of ball-on-flat [12–20], which is not consistent with the actual design of artificial joints. According to the literature [11,12], contact zone kinematics could profoundly influence accumulation, compaction and displacement of the debris particles generated during torsional fretting wear. So, the contact mode, contact stress, torsional fretting wear behavior and damage mechanisms may be different from those in the real environment. Since many artificial joints such as cervical disk and hip joint are designed as ball-on-socket or femoral head-on-acetabular fossa structure, the contact of ball-on-socket model is closer to the real situation than ball-on-flat. However, the torsional wear behavior of UHMWPE ball on titanium socket model has never been studied and clearly discussed before. In addition, the axial rotation displacement is still not made in agreement between the two most commonly used test standards in in vitro wear simulation of total disk prostheses. ISO (International Organization for Standardization) 18192-1 (2011) sets the axial rotation displacement as ±4° while ASTM (American Society of Testing Materials) F2423 (2011) sets it as ±6°. Hence, the effect of axial rotation displacement on wear properties of artificial cervical disks still needs to be clarified.

In this study, an artificial cervical disk was simplified as a ball-on-socket contact configuration with a material combination of Ti6Al4V alloy coated by C-DLC mixed layer and UHMWPE. Its torsional fretting wear behavior under different torsional angular displacement amplitudes was investigated. Finally, the frictional kinetic behavior, damage mechanism, damage region and types of UHMWPE ball and titanium alloy socket were compared with those of ball-on-flat contact configuration and other in vitro cervical prosthesis wear simulations according to the literature in the discussions.

2. Materials and methods

2.1. Ball-on-socket contact configuration

Since a majority of artificial cervical disks such as Activ-C (Aesculap AG, Germany) and Discover-C (Depuy spine, America) were designed as ball-on-socket contact [21,22], a ball-on-socket model was adopted in this investigation to simplify and simulate the artificial cervical disk bearing surface. The ball-on-socket design consisted of a convex shaped inlay made of UHMWPE and a concave shaped superior titanium alloy endplate forming a spherical joint. The schematic and actual pictures of the ball-on-socket contact configuration are shown in Fig. 1. The radius of the ball/socket is 13 mm and the contact area is 26π (~81.7) mm^2 according to the calculation formula of spherical surface area.

The UHMWPE ball was made from powders in a hot-pressing furnace (2T-40, Shanghai, China). The details are as follows. Firstly, a special mold was designed and filled with UHMWPE powders (average grain size: 18.43 μm, relative molecular mass: 6×10^6, density: 0.935 g/cm^3). And the mold was put into the hot-pressing furnace with the pressure at 8 MPa and heated until the temperature reached 200 °C. Then, the pressure was released and the temperature at 200 °C was kept for 90 min. Finally, the samples were naturally cooled in the furnace with the pressure at 10 MPa. The average surface roughness (Ra) of the UHMWPE ball in this study is 0.88 ± 0.09 μm.

The biomedical Ti6Al4V alloy (Baoji Titanium Industry Company Limited, China) sample was firstly machined as a cylinder with a diameter of 30 mm and a thickness of 5 mm. Then, a socket crown was machined and polished with the average surface roughness (Ra) of 0.03 ± 0.01 μm. Finally, the titanium alloy socket was coated with C-DLC mixed layer by a two-step modification process. The details are as follows. Firstly, carbon ion implantation was performed on the Ti6Al4V socket with a dose of 10^{16} ions/cm^2 at 60 keV voltage in an ion implanter (Model: LC-4, Changsha, China). Then, the carbon ion implanted sample was coated by DLC with a deposition bias of 20 kV at 1 Pa pressure for 10 h using plasma enhanced chemical vapor deposition (PECVD) system (DLZ-01 Multi-function ion implantation equipment, Harbin Institute of Technology, China). The flow ratio of C_2H_2 and H_2 gas was 20:1 during the process. The chamber temperature was 400 °C for the C ion implantation process and was 60 °C for the PECVD deposition of the DLC layer. The operating power was 300 W and RF frequency of the plasma source was 13.56 MHz in the PECVD process.

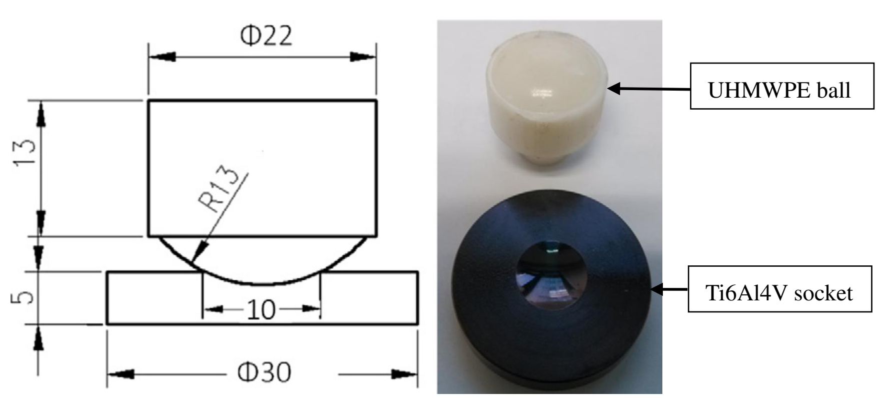

Fig. 1. The schematic and actual pictures of the ball-on-socket contact configuration.